

Multiple factors constrain Ponderosa Pine regeneration 9 years after a mixed severity wildfire in Central Arizona

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Research Article

Keywords: Ponderosa pine, southwest, regeneration, Arizona, drought, climate, wilderness, stand structure

Posted Date: October 6th, 2022

DOI: <https://doi.org/10.21203/rs.3.rs-1847497/v1>

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Abstract

Background: Long lasting drought, climate change and sub-optimal forest conditions are creating more frequent and severe fires in southwestern ponderosa pine (*Pinus ponderosa*) forests. These same conditions make ponderosa pine regeneration difficult as these trees are poorly adapted to establishing and surviving in sustained drought and in large treeless areas. The 2013 Doce fire in the Prescott National Forest burned three quarters of the Granite Mountain Wilderness in Arizona USA, and much of its ponderosa pine forests. Here we report the current state of pine regeneration on Granite Mountain and the conditions of the surviving stands, as well as climate factors relevant to their ability to facilitate regeneration. With unfavorable climate conditions predicted to continue, ponderosa pine regeneration in Xeric Southwestern Pine forests is likely to fail when stand conditions are also unfavorable.

Results: Pine regeneration within the burned area was largely absent. Tree density and basal area were reduced in most fire severity classes. Significant differences in mean annual temperature, maximum vapor pressure deficit, and annual precipitation were identified since the 2000s drought began at the site. The average distance of high severity burn plots to a seed tree is beyond the suggested maximum distance of seed dispersal for ponderosa pine. Calculated establishment rates of ponderosa pine are below required levels for reforestation.

Conclusions: A combination of climate factors and remaining stand structure characteristics is constraining ponderosa pine regeneration in the Granite Mountain Wilderness. With a hotter and drier future predicted, xeric ponderosa pine forests face harsh conditions, especially considering the likelihood of severe wildfires. Appropriate management actions should be taken before wildfires occur to ensure that these xeric forests are given optimal conditions to survive wildfire.

Background

In recent decades, wildfires have been increasing in both size, severity and frequency in the Western United States (Westerling et al. 2006; Dennison et al. 2014; Singleton et al. 2019). In the southwestern USA (Arizona, New Mexico, Southwestern Colorado), these fires are associated with loss of ponderosa pine forest habitat (Owen et al. 2017; Savage and Mast 2005; Leonard et al. 2015; Ouzts et al. 2015; Haffey et al. 2018; Rodman et al. 2020). Ponderosa pine is poorly adapted to regeneration in treeless areas as their fire adaptations, thick insulated bark, self-pruning branches, thick bud scales and protected meristems favor survival during fires rather than regeneration post-fire. Ponderosa pinecones are non-serotinous, trees are non-sprouting and their seeds do not survive in the seed bank for long (Burns and Honkala 1990; Schubert 1974). Therefore, surviving seed trees are critical for determining probable regeneration (Stevens-Rumann and Morgan 2019). For example, Kemp et al. (2019) determined that presence of ponderosa pine seedlings in burned areas was most likely within 60 m of a seed tree, whereafter the likelihood of seedling presence dropped off quickly as the distance to seed tree increased.

Climate is an additional factor that influences regeneration probability (Savage et al. 1996). With the Southwest facing unprecedented and unrelenting drought, climate predictions indicate shrinking suitable ponderosa pine habitat and increases in drought induced stress and mortality within current forests (Savage and Mast 2005; Coop et al. 2020; Williams et al. 2022). These effects will be seen initially in stands at the edge of the current ponderosa pine habitat suitability niche. The 2013 Doce Fire on the Prescott National Forest burned 75% of the Granite Mountain Wilderness and 684 ha of remote ponderosa pine forests on its peaks and saddles. This study sought to investigate post-fire ponderosa pine regeneration in these stands, document current conditions in forest patches that remain, and investigate climate trends proposed to affect ponderosa pine regeneration.

Methods

Study Area

Our study area was the site of the Doce Fire within the Granite Mountain Wilderness on the Prescott National Forest (Fig. 1) in west central Arizona (34° 38' 18" N 112° 33' 09" W). The Doce Fire was a human ignited wildfire that started on June 18th, 2013 and burned 2738 ha. The fire burned in primarily in Mogollon Chaparral, Madrean Pinyon-Oak Woodland, *Quercus Turbinella* shrubland alliance, Ponderosa Pine Woodlands, and Dry-mesic mixed conifer at the highest elevations (*Prescott National Forest (N.F.), Timber Management Plan: Environmental Impact Statement* 1976).

Data Collection

LANDFIRE (www.landfire.gov) existing vegetation information from 2010 was used to establish locations of ponderosa pine within the Doce Fire burn area. These areas were then further classified into burn severity classes using the difference normalized burn ratio (Δ -NBR) map from the Monitoring Trends in Burn severity (MTBS) project (Eidenshink et al. 2007). Upon investigating the unburned/low classification in the Δ -NBR map with satellite imagery (Google Earth Engine), we determined that many of these areas were rock scree and therefore decided to combine the Unburned/low and low severity classification (henceforth "low severity"). Within these designated areas, the random point generator tool in ArcGIS Pro (ESRI) was used to generate 18 plot points, 6 plots in low, moderate, and high burn severity. We used historical satellite imagery, most recently from 2012, to verify that the plots generated contained ponderosa pine before the Doce Fire occurred. If these plots did not contain ponderosa pine, a new plot point was generated using the method described above. Plots ranged between 2040 and 2264 meters in elevation.

Field measurements within plots were taken in the spring of 2022, nine years after the Doce Fire burned. At each site, 0.2 ha plots were established and both tree density and diameter at breast height (dbh) were recorded for every living and dead ponderosa pine, snag type (*sensu* USDI National Park Service, n.d.). Dominant understory species were also recorded. Distance to seed tree (m) was recorded at the plot

center in plots where no living overstory trees were identified using a laser rangefinder. We used climate data from PRISM to investigate trends in annual temperature, precipitation, and maximum vapor pressure deficit at the site from 1980 to 2020 (<https://www.prism.oregonstate.edu/>).

At low severity sites, understory species included alderleaf mountain mahogany (*Cercocarpus montanus*), brittlebrush (*Encelia farinosa*), sonoran scrub oak (*Quercus turbinella*), pointleaf manzanita (*Arctostaphylos pungens*), bottlebrush squirreltail grass (*Elymus elymoides*), catclaw acacia, sagebrush (*Artemisia* sp.), sacapellote (*Acourtia microcephala*), foxtail (*Hordeum jubatum*), creeping barberry (*Mahonia repens*), coffeeberry (*Frangula californica*), slender lip fern (*Myriopteris gracilis*) and ponderosa pine litter. At moderately burned sites, prevalent understory species included alderleaf mountain mahogany, black sagebrush (*Artemisia nova*), brittlebrush, sacapellote, brownfoot (*Acourtia wrightii*), white oak (*Quercus arizonica*), alkali sacaton (*Sporobolus airoides*), yerba Santa (*Eriodictyon* sp. Benth.), sacahuista (*Nolina macrocarpa*), yellow foxtail, pointleaf manzanita (*Arctostaphylos pungens*), Agave (*Agavaceae* sp.), alligator Juniper (*Juniperus deppeana*) and ponderosa pine litter. High severity understory species included pointleaf manzanita, sonoran scrub oak, alderleaf mountain mahogany, brittlebrush, and foxtail.

Data Analysis

Basal area and tree density were calculated at all plots. Pre-fire basal area was approximated by combining live and dead tree measurements at each plot. As the surviving trees have had nine years to grow since the fire, we acknowledge that pre-fire basal area is overvalued. Pre-fire tree density was verified by counting crowns from historical satellite images of plots from 2012 in Google Earth Pro. It is not possible to accurately estimate the density of saplings or seedlings as they were not visible in images and most likely burned completely if present. We tested for differences in mean tree density and basal area using Welch's T-test. Regeneration rate was calculated to the decade using the same method utilized by Mast and colleagues (1999). Fall rates were calculated using snag classifications and extrapolated to a decade. PRISM climate data from 1980–2020 was acquired and analyzed in three bins pre drought (1980–1990), drought (2000–2020) and post fire (2013–2020). Analysis of variance (ANOVA) tests with post hoc Tukey-Kramer tests were used to investigate differences between each burn severity group.

Results

In 18 plots, only one ponderosa pine seedling was documented. Additionally, a visual survey of Granite Mountain showed no other seedling in the burn area. The establishment rate was calculated at 0.3 stems $\text{ha}^{-1} \text{decade}^{-1}$. Tree density and basal area were reduced in all burn severity classes. Compared to pre-fire conditions, live tree density was significantly ($p < 0.05$) reduced in all burn severity classes (Table 1). Pre-fire tree density was between 12–30 trees ha^{-1} and post-fire between 0–14 trees ha^{-1} . Basal area was reduced in high and low severity plots but not significantly ($p < 0.05$) in moderate severity plots (Table 1). The fall rate for fire killed ponderosa pine trees was calculated at 10.1 trees $\text{ha}^{-1} \text{decade}^{-1}$ or 8% yr^{-1} . The mean distance from treeless plots to the nearest tree was 26.6 (SE = 6.51) m in moderate

severity plots and 68.12 (SE = 19.36) m in high severity plots. Forest stand structure are illustrated with photographs taken in April 2022 for high severity (Fig. 2) and for low to moderate severity (Fig. 3).

Analysis of PRISM climate data of the site from 1980–2020 indicated significant differences in maximum annual temperature, maximum VPD and average annual precipitation (Table 2). Maximum VPD was significantly different ($F_{2,46} = 17.90$, $P \leq 0.001$) between 1980–1999 and both 2000–2020 and 2013–2020. Means were also different when annual precipitation ($F_{2,46} = 8.26$, $P \leq 0.001$) and annual temperature were considered ($F_{2,46} = 24.41$, $P \leq 0.001$).

Table 1. Stand structure of plots on Granite Mountain with paired t-test results and significance in bold. Mean tree density and mean basal area with standard error in parenthesis are reported. Post-fire values were measured in 2022, nine years after the Doce fire burned.

Fire Severity	Pre-fire Tree Density (Stems ha ⁻¹)	Post-fire Tree Density (Stems ha ⁻¹)	P	Pre-fire Basal Area (m ² ha ⁻¹)	Post-fire Basal Area (m ² ha ⁻¹)	P
Low	23.3 (5.3)	14.0 (3.7)	0.020	2.55 (0.3)	1.87 (0.6)	0.010
Moderate	12.0 (3.0)	6.6(3.1)	0.002	1.71 (0.4)	0.79 (0.4)	0.060
High	25.0 (8.6)	0 (0)	0.010	1.83 (0.7)	0 (0)	0.020

Table 2. PRISM climate data at the site was compared. Pre drought (1980-1999), drought (2000-2020) and postfire (2013-2020) were selected for ANOVA.

Years	Mean Max VPD (hPA)	Mean Temperature (C°)	Mean Precipitation mm
1980-1999	18.67 (0.27)	11.33 (0.11)	600.64 (27.79)
2000-2020	20.57 (0.22)	12.22 (0.11)	451.65 (29.25)
2013-2020	20.68 (0.40)	12.55 (0.19)	522.33 (52.23)
ANOVA	$F_{2,46} = 17.90$	$F_{2,46} = 24.41$	$F_{2,46} = 8.26$
P	≤ 0.001	≤ 0.001	≤ 0.001

Discussion

The discovery that regeneration of ponderosa pine is largely absent in the Doce Fire scar is consistent with similar studies in the southwest where little to no regeneration has occurred (Haffey et al. 2018;

Leonard et al. 2015; Ouzts et al. 2015; Stoddard et al. 2018). The calculated regeneration rate of 0.3 stems $\text{ha}^{-1} \text{decade}^{-1}$ is well below the requisite rate of 3.6 stems $\text{ha}^{-1} \text{decade}^{-1}$ to maintain pre-settlement ponderosa pine forest density, calling into question the future of ponderosa pine at this site (Mast et al. 1999). The combination of poor remaining forest structure and unrelenting drought means that regeneration potential can be considered low. Low precipitation, high VPD and large treeless areas have all been implicated in limiting ponderosa pine regeneration (Korb et al. 2019; Stevens-Rumann and Morgan 2019). Establishment and survival of ponderosa pines is dependent on a number of factors including ample precipitation, seed production, climate, an optimal basal area and predation (Kolb et al. 2020). Opportunities for regeneration pulses will be reduced as the climate becomes less favorable.

Ongoing drought conditions make ponderosa pine regeneration challenging. Savage and colleagues (Savage et al. 2013) found that the timing of high severity fires during the 1950s drought in New Mexico affected ponderosa pine regeneration and post fire land type conversion. Sites that burned towards the end of drought had more opportunities to support regeneration than those in the middle or beginning. Earlier burns had converted to grasslands or woody shrub cover. The southwestern United States is currently undergoing the most severe drought of the last 1,200 years (Williams et al. 2022) implicating that type conversions are likely to become more common.

Increased temperatures identified over the last 20 years are correlated with elevated Vapor Pressure Deficit (VPD). High VPD causes physiological changes in plants, namely the closing of stomata to reduce the rapid loss of moisture and increased rates of soil moisture loss (Grossiord et al. 2020). High VPD dries out seedlings, especially in the first 2 years of growth (Shepperd et al. 2006). VPD has also been implicated in loss of growth viability and decreases in forest health globally (Restaino et al. 2016; Davis et al. 2019). Climate predictions in the southwest suggest that without decreases in temperature and VPD, continued and increased drought-stressed forests and mortality will alter forest structure and distribution (Williams et al. 2013). We identified significantly higher VPD at the site since 1999. Seedlings that do establish at the site therefore will have a difficult time surviving and may succumb to desiccation or drought related mortality.

Distance to seed source is a strong determinant in predicting regeneration ability (Korb et al. 2019). The mean distance to seed source in high severity burn areas sampled was 68 m, although many unsampled areas are much further. 60 m from a seed tree has been identified in several studies as a threshold at which ponderosa pine regeneration is unlikely to occur (Bonnet et al. 2005; Kemp et al. 2016). Many once forested areas on Granite Mountain exceed this threshold adding an additional unfavorable factor when considering the potential for natural reforestation.

The basal area of surviving stands between 1.25 and 0.5 m^2ha^{-1} is sub-optimal for facilitating seedling survival in Northern Arizona. Kolb and colleagues (2020) found that 23 m^2ha^{-1} was the optimal basal area for survivability of seedlings. Low basal area is associated with increased understory competition as well as higher surface temperatures are all conditions that contribute to lower likelihood of natural regeneration. Current basal area is also below suggested historical reference conditions, although this

was also the case in our calculated pre-fire stand structure and suggests there is more variability in pre-settlement ponderosa pine forest structure than current literature suggests (Reynolds et al. 2013).

The fall rate determines how rapidly killed trees will become ground fuels. At this site, the fall rate was determined to be $10.1 \text{ trees ha}^{-1} \text{ decade}^{-1}$. In other words, given the pre-fire tree density and current distribution of standing dead to surface dead, standing snags fall at a rate of $8\% \text{ yr}^{-1}$. Dead trees residing on the surface influence both the predicted fire behavior and severity and also play important roles as nurse objects to facilitate regeneration (Brown et al. 2003). Fallen trees and other nurse objects have been shown to reduce surface temperatures, by shading more soil, and improving soil moisture compared to sites where dead trees were removed by salvage logging (Castro et al. 2011). In the southwest, nurse logs were found within 30 cm of 44% of all identified ponderosa pine seedlings in eight fire scars, demonstrating their importance in providing microhabitats suitable for regeneration (Haffey et al. 2018). Unfortunately, within the Doce fire scar, while rapid rates have already moved the majority of snags to the surface, many of these areas remain distant from a seed tree. The fallen snags, however, could be beneficial if tree planting operations were untaken at the site as the habitat, they provide may increase the likelihood of survival.

Recently, several studies have identified both preemptive and post fire management actions that can improve forest health in ponderosa pine forests undergoing significant challenges related to climate induced stressors. Several strategies for maintaining forested refugia in large burn scars includes post fire fuels reduction (pile burning, mastication, natural fire use), edge hardening, nucleation planting and landscape scale forest restoration (Stevens et al. 2021). Tree planting can be an effective method for re-establishing forests where natural seed dispersal opportunities are limited however, post-fire successional species type and distribution can influence survival rates of planted trees (Crockett and Hurteau 2022). Identifying and utilizing seedlings more strongly adapted to surviving in hotter and drier temperatures can influence the chances of survival when planting is required. In one study, seeds collected from the hottest and most arid southwestern ponderosa pine forests survived better than those from wet, cool sites (Kolb et al. 2019). Active management will be necessary to re-establish destroyed ponderosa pine forests in areas where natural regeneration is unlikely due to poor remaining stand structure, large high severity burn areas and a hotter and drier climate.

Conclusion

Currently, there is not enough regeneration of ponderosa pine to support the reforestation of areas burned in the 2013 Doce Fire. A combination of factors including drought, high temperatures, high maximum VPD, low basal area of surviving stands, and high distances to mature trees will constrain regeneration. Without intervention, conversion of these once forested areas to other land cover types appears likely. Both stand structure and climate must interact favorably to create conditions conducive for natural ponderosa pine reforestation. Xeric ponderosa pine forest is the “canary in the coalmine” for climate induced loss of habitat.

Abbreviations

ANOVA

analysis of variance

BA

basal area (m^2/ha)

DBH

diameter of a tree measured at breast height (1.37 meters)

Δ -NBR

difference normalized burn ratio

VPD

vapor pressure deficit (hPA)

Declarations

Ethics approval and consent to participate

Not applicable

Consent for publication

Not applicable

Availability of data and material

Please contact author for data requests

Competing interests

The authors declare that they have no competing interests.

Funding

No funding source to acknowledge

Author's contributions

JWC and EKS participated in the study conception and design and development of analysis approach.

JWC lead field data collection, data management, identification of specimens. JWC wrote the first version of the manuscript with review and complements from EKS. Both authors provided a critical review and both authors approved the final manuscript version.

Acknowledgements

None

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Figures

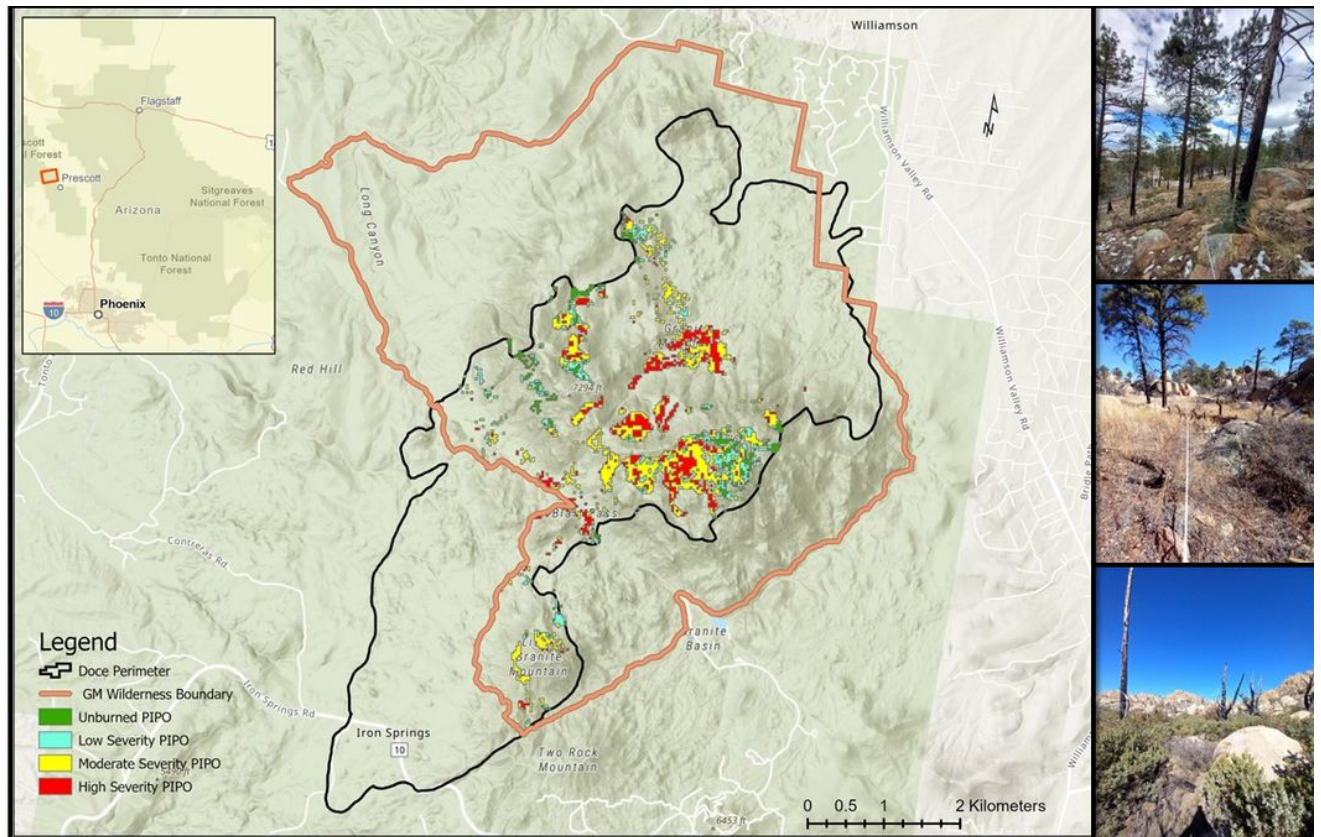


Figure 1

Location of the Doce Fire within the Granite Mountain Wilderness on the Prescott National Forest that burned in June 2013. Burn severity for the ponderosa pine woodlands are mapped by severity class. The photos to the left illustrate from top to bottom low, moderate, and high severity sites



Figure 2

High severity burn areas sampled had no surviving overstory ponderosa pine, as seen on the western face of Granite Mountain. The photo was taken in 2022, nine years after the Doce Fire.



Figure 3

A low/moderately burned ponderosa pine stand on the northeastern face of Granite Mountain. The only identified ponderosa pine seedling in this study is located in this stand, which also contains Douglas-fir and alligator juniper. The photo was taken in 2022, nine years after the Doce Fire.